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# Growing and testing mycelium bricks as building insulation materials

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**Abstract.** In order to improve energy performance of buildings, insulation materials (such as mineral glass and rock wools, or fossil fuel-based plastic foams) are being used in increasing quantities, which may lead to potential problem with materials depletions and landfill disposal. One sustainable solution suggested is the use of bio-based, biodegradable materials. A number of attempts have been made to develop biomaterials, such as sheep wood, hemcrete or recycled papers. In this paper, a novel type of bio insulation materials – mycelium is examined. The aim is to produce mycelium materials that could be used as insulations. The bio-based material was required to have properties that matched existing alternatives, such as expanded polystyrene, in terms of physical and mechanical characteristics but with an enhanced level of biodegradability. The testing data showed mycelium bricks exhibited good thermal performance. Future work is planned to improve growing process and thermal performance of the mycelium bricks.

## 1. Introduction

Building insulation plays an important role in improving thermal comfort, health and wellbeing of occupants and reducing heating and cooling energy consumptions, carbon emissions and pollutions [1]. However, most of the buildings insulation materials are manufactured using mined and/or fossil fuel-based materials. In this study, we prepared and tested alternative building insulation materials. We selected three species of basidiomycete fungi and used these to grow mycelium bricks on straw waste. Dual-needle probes are used to measure the thermal conductivity and specific heat capacity. It is based on the transient hot wire method in which a small constant heat pulse is supplied to the sample through a heating probe and the rise in temperature is noted by a sensing probe located at a fix distance from the heating probe. We carried out preliminary thermal characterisation tests. The paper concludes with a discussion on future research needs in this area.

## 2. Fungi species and growing process

### 2.1. Basic information about the fungi

The realm of Fungi is a diverse kingdom, with members of the phylum Basidiomycota exhibiting a range of ecological strategies, ranging from the familiar edible or poisonous mushrooms to human and plant pathogens. However, a key feature restricted to certain members of this phylum is the ability to



decay lignin and as such a wide range of basidiomycetes have been studied as agents of wood decay. In the past, most research activities have focused on elucidating the mechanisms of lignocellulose degradation both in an ecological context and also to mitigate the harmful effects of such fungi for instance in wooden buildings etc. [2]. The use of wood decay fungi for colonizing waste materials has received limited attention. Here we explore the potential of waste materials partially colonized by white rot fungi as potential thermal insulation material.

## 2.2. Species selected in this experiment

Three species of basidiomycete fungi (order Polyporales) were chosen because they were known to grow quickly on agar media and to be powerful colonisers and degraders of lignocellulose (table 1). All were originally isolated from trees (both live and dead) in the Nile Delta region of Egypt (El-Gharabawy, 2016). All grew rapidly (8.7-13 mm/day at 25°C on 3% Dark Malt Extract Agar [DMEA]).

**Table 1.** Species.

Code	Species	Descriptions
<b>OXY</b>	<i>Oxyporus latermarginatus</i>	Isolate EM26 from cut dead stump of <i>Mangifera indica</i>
<b>MEG</b>	<i>Megasporoporia minor</i>	Isolate MG65 from living <i>Salix alba</i> tree
<b>GAN</b>	<i>Ganoderma resinaceum</i>	Isolate GR33 from living <i>Casuarina equisetifolia</i> tree

## 2.3. Growing environment, substrate, nutrient, and growing process

In this section, basic information regarding fungi, and growing environment, and the end products will be described. Fungal cultures were routinely cultivated on 3% DMEA and incubated at 28°C. For the bulking up of inoculum, 10 g rye grains and 10 ml water were placed in a 25 ml glass (Universal) vial and sterilised by autoclaving (115°C/15 min). When cooled the rye grains were inoculated at 28°C with three plugs of mycelium from agar plate cultures, and the lids capped loosely to allow air exchange. After 14 days, the rye grains were well colonised and then used to inoculated wheat straw cultures. The orientation of straws was randomly placed (as shown in figure 1).

Straw cultures were established in polycarbonate plant tissue culture vials (Magenta GA7; 77x77x97 mm; Sigma). Wheat straw was cut to 3-4 cm lengths and dispensed 20 g per vial with 40 ml water added to each vial. Vials were autoclaved (115°C/15 min) and after cooling down, inoculated with 6-8 colonised rye grains spread around the vial. Cultures were incubated at 28°C for 8 weeks with the vial lids slightly opened to allow air exchange. No any resins are used in the process. Straw blocks were removed from the culture vials and dried at 70°C. They showed some loss of fresh weight, dry weight, and differences in density as in table 2:

**Table 2.** Weight losses, volume, and density.

FUNGI SPECIES	Fresh weight <sup>1</sup> (g)	Fresh weight loss (%)	Dry weight (g)	Dry weight loss (%)	Dry Mass Volume (cm <sup>3</sup> )	DENSITY (KG/M <sup>3</sup> )
<b>OXY</b>	37.2	38.0	15.61	25.1	285.8	<b>51.098</b>
<b>MEG</b>	37.3	37.8	17.55	12.5	283.2	<b>61.967</b>
<b>GAN</b>	<b>35.6</b>	<b>40.1</b>	<b>14.56</b>	<b>27.5</b>	<b>253.3</b>	<b>57.452</b>

<sup>1</sup>Initial fresh weight was 60 g (20g wheat straw/40 g water)

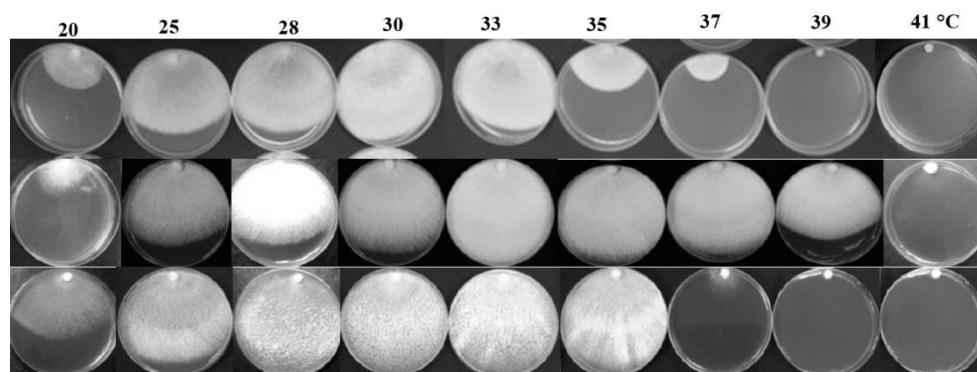
The appearance of the colonized wheat straw differed between the three species. GAN preferentially colonized the outer parts of the substrate. The exact reason for this is not clear but may show an avoidance of areas of higher CO<sub>2</sub> concentration (with CO<sub>2</sub> formed from fungal metabolism). However, the pattern of mycelial growth may be in response to other gradients within the culture vessel (e.g. moisture, O<sub>2</sub>). Different species also exhibit different wood colonization strategies for other reasons, for example to protect outer boundaries of the colony from attack by other fungi. In any event colonization of the core of the wheat straw block was poorer than for other species and this is reflected in the physical properties of the mycelial block. In terms of substrate decay, GAN exhibited the greatest dry weight loss over the 8 week incubation period, consistent with the pattern of enzyme production on ashwood sawdust that was observed (as shown in table 3) for this isolate by El-Gharabawy [3].

The pattern of wheat straw colonization was similar for OXY and MEG with even more colonization across the centre of the block. In both cases there was more growth at the top of the culture vessel (where the air vents were located). In the case of OXY, initial growth (weeks 1-2) was predominantly visible at the top of the culture vessel with colonization of the lower layers of wheat straw occurring later.

**Table 3.** Growth rates reproduced from [3]

CODE	Species	RGR Radial Growth Rate (mm/d)	AREA (LAT/LONG)
OXY	<i>Oxyporus latermarginatus</i>	13.0	<b>DAMIETTA; EI-SENANIAH (N 31.2611 E31.4648)</b>
MEG	<i>Megaporoporia minor</i>	8.7	<b>DAKAHLIA; MANSOURA UNIV.(N31.0403, E31.3590)</b>
GAN	<i>GANODERMA RESINACEUM</i>	10.4	<b>DAKAHLIA;DEKERNIS (N31.0637, E31.6577)</b>

As shown in figure 1, the three isolates used here grow maximally at 30°C (GAN and OXY) or 33°C (MEG) on agar plates so in all three cases incubation at higher temperatures would likely lead to more rapid substrate colonisation (and thereby shorter incubation periods for mycelial block preparation –maybe as low as 4 weeks). Growth at different temperatures may also alter patterns of ligninolytic enzyme production which in turn would alter patterns of substrate decay and possibly lead to differences in the thermal properties of the mycelial blocks. The final mycelium thermal blocks are shown in figure 2.



**Figure 1.** Radial growth rate of isolates at different temperatures (upper row is GAN, middle is MEG, lower is OXY).





**Figure 2.** Three Specimens.

### 3. Preliminary transient thermal testing

#### 3.1. Transient thermal measurement approach

In order to determine basic thermal characteristics (i.e. thermal conductivity  $k$ -value and specific heat capacity) of the mycelium blocks, KD-2 Pro thermal analyser (model KD-2 Pro, Decagon Device, Inc.) was used as shown in figure 3. High accuracy, shorter measurement time and easy to use are the main advantages of this method [4]. There are commonly two types of thermal needle probe: single and dual-needle. In this study, we have used dual-needle probe. Heat is applied to the heated needle for a set heating time,  $t_h$ , and temperature is measured in the monitoring needle, 6 mm distant during heating and during the cooling period following heating. The readings are then processed by subtracting the ambient temperature at time 0, multiplying by  $4\pi$  and dividing by the heat per unit length,  $q$ . The resulting data are then fitted to the following equations [5] using a nonlinear least squares procedure [6] which is calculated using the KD 2 Pro Analyser.

$$T^* = b_0 t + b_1 Ei\left(\frac{b_2}{t}\right) \quad (1)$$

$$T^* = b_0 t + b_1 \left\{ Ei\left(\frac{b_2}{t}\right) - Ei\left[\frac{b_2}{t - t_h}\right] \right\} \quad (2)$$

where:

$$T^* = \frac{4\pi(T - T_0)}{q} \quad (3)$$

$Ei$  is the exponential integral, and  $b_0$ ,  $b_1$  and  $b_2$  are the constants to be established.  $T_0$  is the temperature at the start of the measurement and  $q$  is the heat input. The first equation applies for the first  $t_h$  seconds, while the heat is on. The second equation applies when the heat is off. Compute thermal conductivity from Equation 4 and diffusivity from 5.

$$k = \frac{1}{b_1} \quad (4)$$

$$D = \frac{r^2}{4b_2} \quad (5)$$

where,  $k$  is thermal conductivity,  $D$  is specific heat capacity,  $r$  is the distance between the heater and the sensor where temperature is measured.



**Figure 3.** Thermal properties measurement.

### 3.2. Preliminary thermal test results and limitations

Four tests were carried to each specimen placing the dual needle probes in different directions. The average thermal conductivity and specific heat capacity readings are listed in table 4. Thermal conductivity measures the ease with which heat can travel through a material by conduction. Conduction is the main form of heat transfer through insulation. The lower the figure, the better the performance. In general, a good insulator has a higher Specific Heat Capacity because it takes time to absorb more heat before it actually heats up (temperature rising) to transfer the heat. High Specific Heat Capacity is a feature of materials providing Thermal Mass or Thermal Buffering (Decrement Delay). Based on this experiment, OXY has the best thermal insulation performance (lowest thermal conductivity). GAN has the worst thermal insulation performance (i.e. higher thermal conductivity and lowest specific heat capacity).

**TABLE 4.** Thermal performance.

	Thermal conductivity (W/(mK))	Specific Heat Capacity MJ/(m <sup>3</sup> *k)
<b>OXY</b>	0.078	0.418
<b>MEG</b>	0.079	0.501
<b>GAN</b>	0.081	0.369

Nevertheless, the measured thermal conductivities of these three specimens measured in this paper are similar (0.074-0.087 W/mK). A study demonstrated that the decrease of the thermal conductivity of a hay bio-composite is proportional to the decrease of its bulk density, the latter depending on the increase of fibres in the mix [4]. Comparing with other light weight synthetic insulation materials, such as polystyrene (density 28–45 kg/m<sup>3</sup>), thermal conductivity varies between 0.029 and 0.039 W/mK [7] [8]. However, the mycelium bricks is performing better than some other biocomposite materials, such as raisin-based bio-composite 0.09179 W/mK to 0.1534 W/mK [9].

Transient thermal analyses have been utilized in a number of porous insulation materials studies [10-12], however, it should be noted the high porosity of the mycelium materials tested in this study may cause readings to become inaccurate, future calibration and steady-state testing, such as guarded hot plate or hot box may be needed.

## 4. Discussion and conclusions

### 4.1. Selection of fungal species, growing substrates and growing environment

From this study, it can be seen that different species have dramatically different growth patterns within the substrate and bonding. Thus, it is important to select appropriate fungi species to form building insulation materials. In choosing suitable fungi, several factors must be considered: rapid mycelial growth to bind the substrate is desirable but rapid rates of substrate decay (as found here for GAN) are less desirable (potentially weakening the blocks). Even growth at the edges and in the middle of the substrate blocks is also desirable (as shown here for OXY and MEG). These patterns of growth presumably reflect the nature of substrate colonisation by these fungi in nature. El-Gharabawy [3] investigated the spatial patterns of enzyme production by these three fungi on cellophane strips. MEG and OXY produced greatest levels of ligninolytic activity (bleaching of dye) in older zones of mycelial growth, whereas GAN generally secreted these enzymes in a more patchy manner (and less so in areas initially colonised).

### 4.2. Improvement of the growing process

The cultures used here originated from a warm subtropical climate (Nile Delta region, Egypt) and all three grow well at 33°C so could potentially be grown at 5°C warmer than the temperature used for these trials –allowing more rapid colonisation of straw or other substrate, possibly in as little as 4 weeks.

Choice of fungi species also needs to consider the degradation rate of straw (as main type of biomass residuals). It is desirable to have rapid colonisation of straw or other lignocellulosic substrate. However, excessive degradation of the substrate could lead to weakening of the straw block. The isolates differ in their growth rates on agar and also on wood but these growth rates do not necessarily correlate with the extent of dry weight loss. This is because these fungi differ in their colonisation strategies.

Currently the authors are investigating a number of approaches to improve the thermal insulation performance of the light weight mycelium materials. Future experiments are needed to improve the density of the substrates using fine powder, higher density material to increase the overall weight providing 'low' thermal diffusivity and 'high' thermal mass in order to create a nature-based solution to the built environment [13]. Based on the transient thermal conductivity tests, all three specimens exhibit relatively similar thermal characteristics. There is no significant difference between the three specimens based on this type of tests, the next stage is to carry out research on fireproofing methods (e.g. adding flame retardants or gypsum and cementitious plasters).

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